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THE SN 2008S PROGENITOR STAR: GONE OR AGAIN SELF-OBSCURED?

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ABSTRACT

We obtained late-time optical and near-IR imaging of SN 2008S with the Large Binocular Telescope (LBT). We find that (1) it is again invisible at optical ($UBVR$) wavelengths to magnitude limits of approximately 25 mag, and (2) while detected in the near-IR (HK) at approximately 20 mag, it is fading rapidly. The near-IR detections in March and May 2010 are consistent with dust emission at a blackbody temperature of $T \simeq 900$ K and a total luminosity of $L \simeq 40000\, L_\odot$, comparable to the luminosity of the obscured progenitor star. If it is a supernova, the near-IR emission is likely due to shock heated dust since the elapsed time from peak is too long to support a near-IR dust echo and the decline in luminosity is shallower than the ^{56}Co slope. If it is reprocessed emission from a surviving progenitor, a dust photosphere must have reestablished itself closer to the star than before the transient (~ 40 AU rather than 150 AU), unless there is a second, cooler dust component that dominates at mid-IR wavelengths. The continued rapid fading at roughly constant temperature favors transient emission, but the SED peaks in the mid-IR and future Spitzer observations will be needed to close the case.

Subject headings: stars: evolution – stars: supergiants – supernovae:individual (SN 2008S)

1. INTRODUCTION

SN 2008S is one of the most mysterious optical transients created by a massive star in the last decade. It was discovered in February 2008 by Arbour & Boles (2008) in the prolific supernova factory NGC 6946. It was initially classified as a likely "supernova impostor" due to its faint absolute peak magnitude ($M_V \sim -13$ mag) and optical spectra dominated by narrow Balmer and [Ca II] lines in emission (Stanishev et al. 2008; Steele et al. 2008). NGC 6946 had been observed by the Large Binocular Telescope (LBT) the previous year, and the key piece of evidence from these observations was that there was no optical progenitor (Prieto et al. 2008), which was surprising since the "supernova impostors" are believed to be eruptions from very massive (> 20-$30\, M_\odot$), evolved stars (e.g., Smith et al. 2010 and references therein) that should have been easily visible in the LBT observations.

The only means of having an optical eruption from a massive star and an invisible progenitor is for the star to be self-obscured by dust that is largely destroyed by the transient. This possibility was confirmed when Prieto et al. (2008) found the progenitor star as a $\log L/L_\odot \simeq 4.5$, $T \simeq 440$ K blackbody in archival Spitzer data. This luminosity is comparable to that of an evolved $\sim 10\, M_\odot$ star, and is well below that corresponding to the more massive stars thought to be required for non-supernova eruptions. Subsequent analyses of the progenitor by Botticella et al. (2009) and Wesson et al. (2010) were consistent with those by Prieto et al. (2008).

More remarkably, an almost identical event then occurred in NGC 300 (Monard 2008). The progenitor was invisible in the optical to even tighter limits (Berger & Soderberg 2008; Bond et al. 2009; Berger et al. 2009), but we again found the progenitor as a self-obscured star of similar luminosity and (dust photosphere) temperature in Spitzer mid-IR data (Prieto 2008; Thompson et al. 2009). A subsequent analysis of the progenitor by Berger et al. (2009) agreed with our estimates, and an investigation of the progenitor based on its neighboring stars by Gogarten et al. (2009) was consistent with the progenitor being a massive star of order 10-20 $M_\odot$, where the analysis favored the upper portions of this range but, strictly speaking, the method only provides an upper mass bound.

In Thompson et al. (2009) we surveyed the galaxy M33 for mid-IR sources with similar properties to these progenitors and found that they were astonishingly rare, with only a few such sources in the entire galaxy. In the mid-IR, these sources have the properties of super-AGB stars, with properties distinct from other classes of massive stars such as LBVs and red supergiants. The rarity of these sources compared to all massive stars, confirmed in our survey of additional galaxies (Khan et al. 2010), means that the progenitors of the transients are a very short lived ($\sim 10^4$ years) phase in the evolution of these massive stars and that there is a causal connection between obscuration and explosion.

Thompson et al. (2009) concluded that there are a number of possible mechanisms to explain the nature of these transients and their progenitors: (1) massive white-dwarf birth; (2) electron-capture supernova; (3) intrinsically low-luminosity iron core-collapse supernova; and (4) massive star outbursts. Debates about these possible origins have been raging ever since then, based both on theoretical and observational arguments. They are basically divided into the (some kind of) supernova camp (Prieto et al. 2008; Botticella et al. 2009; Pumo et al. 2009) and the (some kind of) massive star outburst camp (Berger et al. 2009; Smith et al. 2009; Bond et al. 2009; Kashi et al. 2010). The outburst camp generally argues that the progenitor was not a $\sim 10\, M_\odot$ super-AGB star but a more massive $15-20\, M_\odot$ star (supported by Gogarten et al. 2009), despite their position at the red, high luminos-

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TABLE 1
LBT MAGNITUDES OF SN 2008S

Date (UT)	MJD	*Us* (mag)	*B* (mag)	*V* (mag)	*R* (mag)	*H* (mag)	*K* (mag)
2008-05-03	54589.4	21.49 ± 0.07	20.86 ± 0.03	19.46 ± 0.04	18.47 ± 0.03	···	···
2008-05-04	54590.4	21.52 ± 0.08	20.91 ± 0.03	···	18.48 ± 0.03	···	···
2008-07-05	54652.4	22.72 ± 0.07	22.27 ± 0.03	21.16 ± 0.04	20.03 ± 0.04	···	···
2008-11-22	54792.1	···	23.59 ± 0.05	22.50 ± 0.05	···	···	···
2008-11-23	54793.1	···	23.58 ± 0.06	22.56 ± 0.05	···	···	···
2008-11-24	54794.1	···	23.45 ± 0.05	22.45 ± 0.05	···	···	···
2008-11-25	54795.1	···	23.54 ± 0.06	22.60 ± 0.05	···	···	···
2009-03-25	54915.5	< 24.1	< 25.6	< 24.8	23.10 ± 0.07	···	···
2009-10-20	55124.1	< 25.2	< 25.9	< 25.7	< 25.1	···	···
2009-10-22	55126.1	< 24.9	< 25.9	< 25.6	< 25.1	···	···
2009-12-17	55182.0	···	···	···	···	20.31 ± 0.14	···
2010-03-17	55272.5	···	···	···	···	< 21.4	19.23 ± 0.09
2010-03-18	55237.5	< 24.6	< 25.3	< 25.4	< 24.9	···	···
2010-05-17	55333.4	···	···	···	···	···	20.27 ± 0.15

All the magnitude upper limits are 3σ. The estimated start date of the transient is MJD 54485.5 ± 4 (Botticella et al. 2009). *B*, *V* and *R* are Bessel filters, *Us* is a high throughput *U*-band interference filter.

ity end of the AGB sequence in mid-IR color-magnitude diagrams (Thompson et al. 2009; Khan et al. 2010) and the low mass compared to typical stars with LBV outbursts (see Smith et al. 2010). The massive-star outburst interpretation is seriously called into question by our Spitzer IRS spectrum of the NGC 300 event (Prieto et al. 2009). The mid-IR spectrum resembles that of carbon-rich proto-planetary nebulae and lacks the silicate-dominated dust features typical of massive star outbursts (e.g., Humphreys et al. 2006). Wesson et al. (2010), analyzing post-event Spitzer observations of SN 2008S, also found that the silicate dust characteristics of high mass stars were inconsistent with the observations. Prieto et al. (2009) also note that proto-planetary nebulae (initial masses $\lesssim 8\,M_\odot$) have most of the optical spectral features that led Smith et al. (2009), Bond et al. (2009) and Berger et al. (2009) to argue for an outburst from a more massive ($\sim 20\,M_\odot$) star. Since "Type IIn" optical spectroscopic properties are seen in some proto-planetary nebulae, massive supergiants, supernova impostors, and the genuine, but very diverse, Type IIn supernovae, they appear only to be a diagnostic for the presence of strong interactions between ejecta and a dense circumstellar medium rather than a diagnostic for the source of the ejecta.

In the end, however, the question is easy to answer – either the stars survived, or they did not. We have been following the SN 2008S event with the LBT in both the optical and near-IR, and here we report that the source is again too faint to detect in the optical, and while detected in the near-IR, it presently is only as luminous as the progenitor and fading rapidly. We describe our observations and results in §2 and discuss their implications in §3.

2. OBSERVATIONS AND RESULTS

The optical observations were done with the Large Binocular Cameras (LBC, Giallongo et al. 2008), using the LBC/Blue camera for *U*, *B* and *V* and the LBC/Red camera for *R*. The pixel scale of the LBC cameras is $0.''22$. Since these observations are part of a program whose overall goal is to use difference imaging to characterize variable sources, the sub-images obtained for each epoch were not dithered and SN 2008S was always located at approximately the same point on Chip 2 of the cameras. Image exposure times were 300 sec, generally with two exposures for *U*, *B* and *V* and 6 exposures for *R*. The near-IR observations were made with LUCIFER (Seifert et al. 2003; Mandel et al. 2008; Ageorges et al. 2010) in the *H* and *K* bands using the F3.75 camera with a pixel scale of $0.''12$. At each dither position we obtained 3 exposures of 33 (10) sec for *H* (*K*) band. We obtained 10 on-source and 6 off-source dither positions in a 2-5-2-5-2 off-on-off-on-off pattern, where the off-source position was shifted 8 arcmin away from the galaxy.

The optical and near-IR data were reduced using standard methods in IRAF. The photometry was obtained using DAOPHOT and ALLSTAR (Stetson 1987; Stetson 1992). The optical data was calibrated using $4-24$ local standards from Welch et al. (2007) for the *V* and *R* bands and from Botticella et al. (2009) for the *U* and *B* bands. The near-IR data were calibrated using $3-6$ 2MASS stars in the field. In both cases we only applied a zero-point offset to convert the instrumental magnitudes into the standard system. The results are presented in Table 1, where the magnitude errors include the uncertainties both in the measurements and in the zero points. In the cases where we do not detect SN 2008S, we place a 3σ upper limit on the magnitude using the standard deviation of the sky in a region around the source.

Figure 1 shows the *H*, *K* and *R*-band light curves from Botticella et al. (2009) and our LBT observations, and Figure 2 shows the current SED. The left panel of Fig. 2 shows the constraints on the progenitor's spectral energy distribution (SED) as compared to typical massive stars. To make the comparison we used a Galactic plus intrinsic extinction of $A_V = 2.13$ mag (Botticella et al. 2009) and the distance of $D = 5.6$ Mpc adopted by Prieto et al. (2008). The data points are converted to a luminosity as $L = 4\pi D^2 \nu F_\nu$. For comparison we show the extincted SEDs of $10\,M_\odot$ and $20\,M_\odot$ red supergiants (RSG) using luminosities and effective temperatures from Marigo et al. (2008), a $20\,M_\odot$ blue supergiant (BSG) modeled on SN1987A, and the blackbody that best fit the SN 2008S progenitor data.

In the optical (*UBVR*), the source is again too faint to correspond to a massive ($> 10\,M_\odot$) evolved star, with limits on its brightness similar to those for the progenitor (see right panel in Fig. 2). The extinction would have to be increased from the $A_V \simeq 2.1$ mag estimated to be present post-explosion (Botticella et al. 2009) to $A_V \sim 3.6-5.8$ mag in order to obscure the models shown in Fig. 2. The transient is still detectable in the near-IR, but it is fading rapidly with a slope of approximately 6 ± 1 mag/year at *K* band that is significantly steeper than the

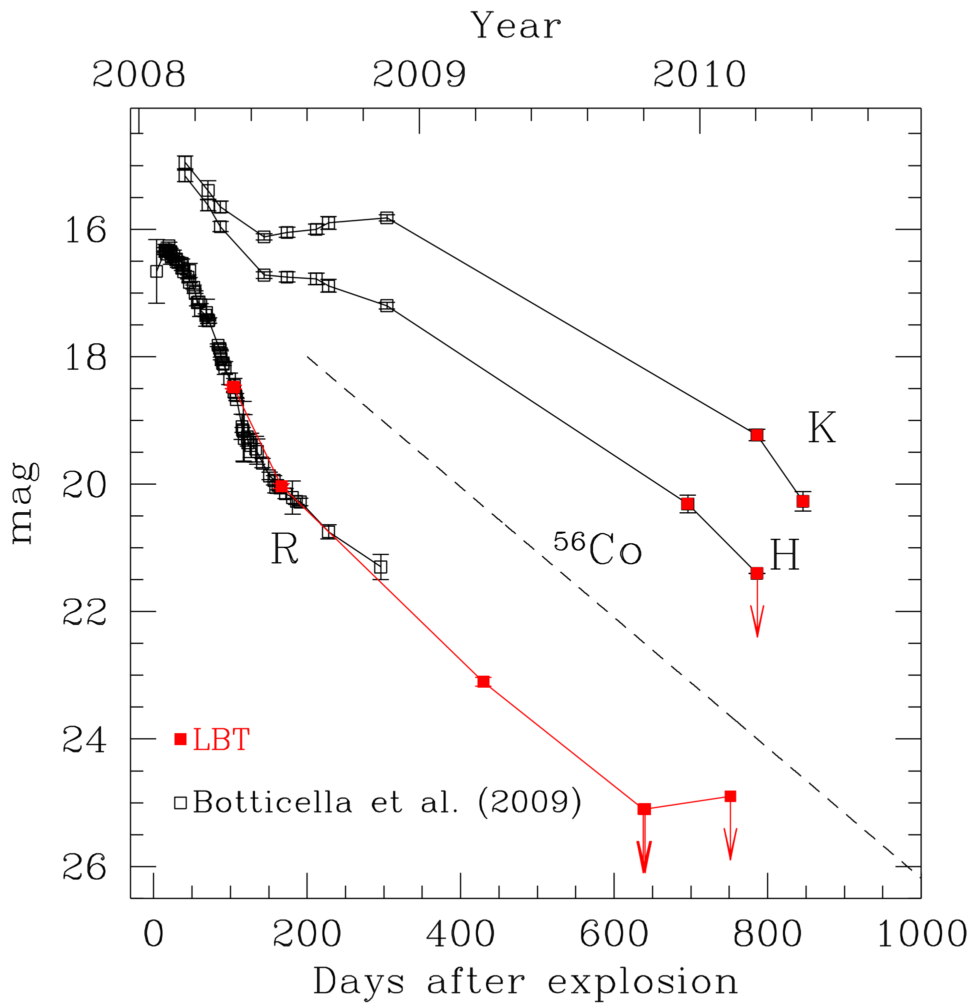

FIG. 1.— The R, H and K-band light curves of SN 2008S from Botticella et al. (2009, open black points) and the Large Binocular Telescope (filled red points). The last R and H-band points are upper limits. The dashed line shows the ^{56}Co decay slope. This should properly be compared with the bolometric light curve, but this will require Spitzer observations. Botticella et al. (2009) found that the bolometric light curve observed after day 120 was slightly shallower than the ^{56}Co decay slope.

mean slope of 2.3 ± 0.1 mag/year between the late phases of the Botticella et al. (2009) light curve and our first LBT observation. The SED is rising to the red with $H-K > 2.2$ mag. If we extrapolate the H-band flux from December 2009 to March 2010 using the slope of the K-band light curve, we estimate $H \simeq 21.9$ mag and thus $H-K \simeq 2.7$ mag, which is significantly redder than the $H-K \simeq 1.4$ mag color in the late phases of Botticella et al. (2009).

We can roughly estimate a temperature and luminosity for the March 2010 epoch. Fitting a blackbody to the measured K-band flux and either the H-band magnitude limit (20.4 mag) or the extrapolated estimate (20.9 mag), we get temperatures of $T \simeq 900$ K and 750 K and luminosities of $L \simeq 68000 L_\odot$ and $130000 L_\odot$, respectively. With a λ^{-1} emissivity law, the estimated temperatures and luminosities are lower, with $T \simeq 800$ K and 700 K and $L \simeq 50000 L_\odot$ and $95000 L_\odot$. With the further fading between March and May 2010, the source luminosity is now comparable to the estimated luminosity $L \simeq 40000 L_\odot$ of the progenitor star (Prieto et al. 2008; Botticella et al. 2009; Wesson et al. 2010).

3. DISCUSSION

Thompson et al. (2009) proposed that SN 2008S and the NGC 300 transient were the archetypes of a new class of transients potentially including the M85 OT-1 transient (Kulkarni et al. 2007; Pastorello et al. 2007), SN 1999bw (Li et al. 2002 and references therein), and now PTF10fqs (Kasliwal et al. 2010). The initial defining characteristics were (1) a dust-enshrouded progenitor without optical counterpart and mid-IR magnitudes that places them at the tip of the AGB sequence in a mid-IR CMD, and (2) a low-luminosity transient ($-13 \gtrsim M_V \gtrsim -15$) with narrow lines in emission in the spectra ($v \lesssim 3000$ km/s), and signs of a circumstellar dust excess at near-IR and mid-IR wavelengths. Examinations of the dust properties (Prieto et al. 2009; Wesson et al. 2010) suggest (3) that the dust is carbonaceous rather than the silicate dust seen in massive stars.

Here we add (4) that the progenitor either does not survive or must return to its dust enshrouded state. As the right panel of Fig. 2 shows, the LBT data already rule out the presence of a massive, evolved star unless it has reconstituted an optically thick, dusty envelope. The present optical limits are some-

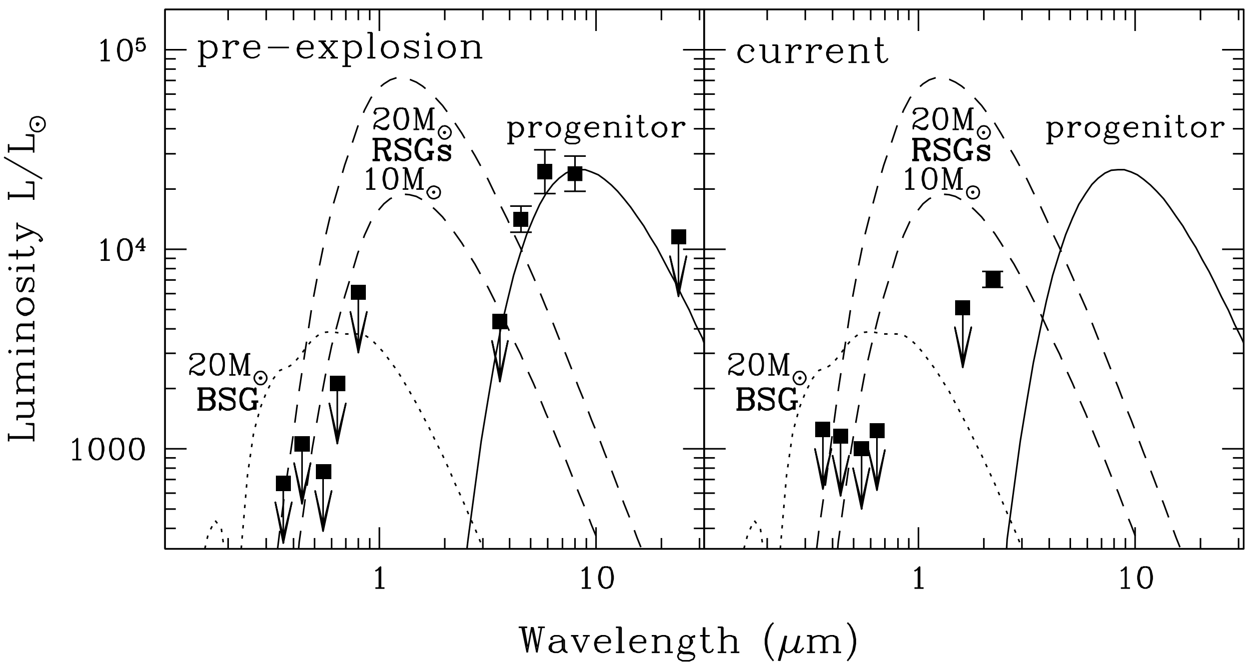

FIG. 2.— The pre-explosion, progenitor SED (left) and the current SED (right) of SN 2008S. The measured magnitudes are converted to fluxes, and these are converted to a luminosity as $L = 4\pi D^2 \nu F_\nu$ where $D = 5.6$ Mpc. The SED models are just blackbodies plus $A_V = 2.13$ mag of total extinction. The $10 M_\odot$ and $20 M_\odot$ red supergiant models (RSG, dashed curves) are from Marigo et al. (2008) and have $T \simeq 3600$ and 3900 K with $\log L/L_\odot = 4.68$ and 5.29, respectively. The blue supergiant model (dotted curve) is based on SN1987A and has $T \simeq 16000$ K and $\log L/L_\odot = 5.0$. The best fit blackbody model (solid curve) for the progenitor has $T = 440$ K and $\log L/L_\odot = 4.54$ (Prieto et al. 2008).

what stronger than those for the progenitor, and the near-IR detections already rule out RSGs more massive than $10 M_\odot$. The total luminosity is now comparable to that of the progenitor and emerges mainly in the mid-IR, but it is also continuing to rapidly fade. Recently, Ohsawa et al. (2010) presented late-time AKARI mid-IR observations of the NGC 300 transient that show the transient is again self-enshrouded with an SED that peaks at $\sim 3-4$ μm ($T \sim 600$ K) and total bolometric luminosity ~ 5 times the luminosity of the mid-IR progenitor.

Let us first consider the possibility that the emission is again due to the progenitor. With roughly the same luminosity but double the temperature, the dust photosphere must be four times closer to the star, at $R_{BB} \simeq 40$ AU [8], although we can't rule out the presence of a cooler dust component that dominates the bolometric luminosity and peaks in the mid-IR. If the optical depth is due to a constant velocity wind, this in turn requires decreasing the mass loss rate $\dot{M}$ (or opacity per unit mass) or increasing the wind velocity v_w by a factor of 4 relative to the progenitor. Producing the near-IR time variability is difficult in this scenario because the characteristic time scale R_{BB}/v_w is ~ 2 years for $v_w \simeq 100$ km/s while the K band flux changed by over a factor of 2 in only 60 days. Thus, it seems unlikely that the system has returned to its pre-transient state.

The rapid fading strongly suggests that the present emission is a continuation of the transient. Since we are now 800 days post explosion, the emission can no longer be explained as an infrared echo. At this point, echos from the transient peak are produced from a minimum distance of $ct/2 \simeq 70000$ AU, and this is simply too distant for dust heated by a transient with a peak luminosity of order $10^7 L_\odot$ (Botticella et al. 2009) to produce significant near-IR emission. While the near-IR emission has roughly decayed at the rate expected from ^{56}Co decay (1.023 mag/100 days, see Fig. 1) the drop in the estimated bolometric luminosity is significantly slower, and it is unclear how the positron heating could be efficiently converted to near-IR emission. The last possibility is shock heating of pre-existing dust. Botticella et al. (2009) and Wesson et al. (2010) estimate that dust survived outside of $1000-2000$ AU, which would be reached after 800 days by a shock moving at $2000-4000$ km/s. Such high velocities were observed in some early line components (Botticella et al. 2009). For the heavy $\dot{M} \sim 10^{-4} M_\odot$/year wind believed to have surrounded the progenitor, the shock luminosity of $(1/2)\dot{M}v_s^3/v_w \sim 10^6 L_\odot$ for $v_w \sim 50$ km/s and $v_s \sim 3000$ km/s, is on the order of what is needed to produce the near-IR emission with $\sim 10\%$ efficiency of emission by shocked dust (Draine 1981). However, this seems a stretch given the time and velocity scales, and it would be simpler to use dust forming in the shocked material as advocated by Botticella et al. (2009).

At its present rate of fading in the near-IR, SN 2008S will effectively be invisible to ground based observatories when it next rises, and finally closing the case will need a combination of HST and, more importantly, Spitzer observations that will be obtained over the next year. The HST observations

[8] There are differences in the sizes quoted for the dust around SN 2008S. Prieto et al. (2008) assume an infinite wind and estimate a photospheric radius of 150 AU, while Botticella et al. (2009) and Wesson et al. (2010) generally discuss the geometric boundaries of the dust distribution.

can detect or rule out the presence of a star in the near-IR to significantly deeper limits than possible from the ground due to both its sensitivity and resolution. With two epochs of data showing some variability, the source can be unambiguously identified even if very faint. The Spitzer observations will accurately determine the temperature and luminosity of the source. If it continues to decay as rapidly as we observed in the near-IR, it should be significantly fainter than the progenitor star in 2011.

These late time observations will be crucial to understanding this new class of transient sources, particularly since it is also possible for the survivor to be fainter than the progenitor in several of the possible scenarios. It could be subluminous as a result of the outburst and then will slowly return to thermal equilibrium (Smith et al. 2009). Or, as suggested by Thompson et al. (2009) and discussed more fully in Prieto et al. (2009), if SN 2008S was the explosive birth of a massive white dwarf, we would expect the bolometric luminosity to approach nearly Eddington for a $\sim 1 M_{\odot}$ object, $\sim 3\times10^{4} L_{\odot}$.

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Facilities: LBT

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